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THESIS

DEMONSTRATION OF WAYPOINT NAVIGATION FOR A SEMI-AUTONOMOUS PROTOTYPE SURF-ZONE ROBOT

by

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June 2006

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DEMONSTRATION OF WAYPOINT NAVIGATION FOR A SEMI–AUTONOMOUS PROTOTYPE SURF–ZONE ROBOT

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ABSTRACT

The objective of the Small Robot Technology (SMART) initiative at the Naval Post Graduate School (NPS) is to develop robots for military uses. One of the goals of this program is to create a surf–zone reconnaissance robot to do beachhead surveillance and mine detection. To this end, a prototype robot was created to test the locomotion and navigation functions which will be used on the surf–zone robot. This work consisted of redesigning the steering mechanism, strengthen the structure, improving the electrical distribution and upgrading the communications hardware. Several tests were conducted on both grass and soft sand to evaluate the performance of the locomotion system and the navigation software. The results demonstrated that the robot functions best in soft sand as expected. However, several serious mechanical design flaws were noticed in the body construction and mechanical systems. These flaws, while not detrimental, did negatively impact the performance of the system. Finally, some suggestions for improving future prototypes are discussed.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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I. INTRODUCTION

A. NPS SMART DEVELOPMENT

The objective of the Small Robot Technology (SMART) initiative at the Naval Post Graduate School (NPS) is to develop robots for military uses. Robots have many advantages attractive to the military, they can be small, covert and most importantly do not put lives at risk.

The surf and littoral combat zones are difficult operational areas for current Navy platforms. These zones are often dangerous as they can be easily mined and obstacles can be erected. In addition, these combat zones are of increasing interest to the Navy as noted in the February 2006 Quadrennial Defense Review [Ref. 11]. The SMART program attempts to improve the Navy's capabilities in these combat zones.

One of the current research programs within SMART is to develop an amphibious and autonomous robotic platform for mine countermeasures and surf zone reconnaissance (see Figure 1). In order to accomplish this, the robot would need to be extremely rugged and mobile as it would need to operate in the harsh environments of salt-water and soft sand. In addition, the robot must be capable of locating, identifying, mapping and relaying the reconnaissance information or mine locations back to another operational asset.

The first prototype autonomous robot, known as Bender© (see Figure 2), was a platform built completely from commercial off the shelf hardware. This platform was used to develop and test sensor systems, the control architecture, computer programs and the graphical user interface. The second generation prototype, named Lopez, was created by LT Jason Ward [Ref. 13]. While this prototype did not have full mobility, the robot began to take its final shape (see Figure 3). Lopez was used to finalize the control interface, test components and increase the motor control of the robot. The current prototype, named Agbot, is a collaberative effort between Case Western Reserve University and NPS. Agbot was built by Richard Bachmann of Case Western based on their previous experience creating highly mobile robots. The robot was designed to work in soft soils encountered in agricultural settings and so the robot can easily adapt to working in sand. Agbot has an aluminum chassis and features

Figure 1. An artists concept of the final design in operation (From [Ref. 2]).

a much more powerful motor than the previous prototype. Agbot is used to finalize the hardware implementation, test the autonomy software and test the platform's mobility on different types of terrain (see Figure 4).

Figure 2. The Bender prototype robot.

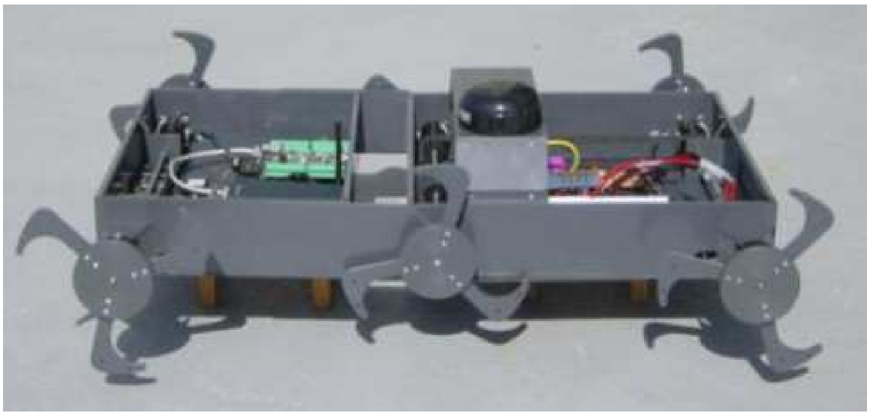

Figure 3. Lopez.

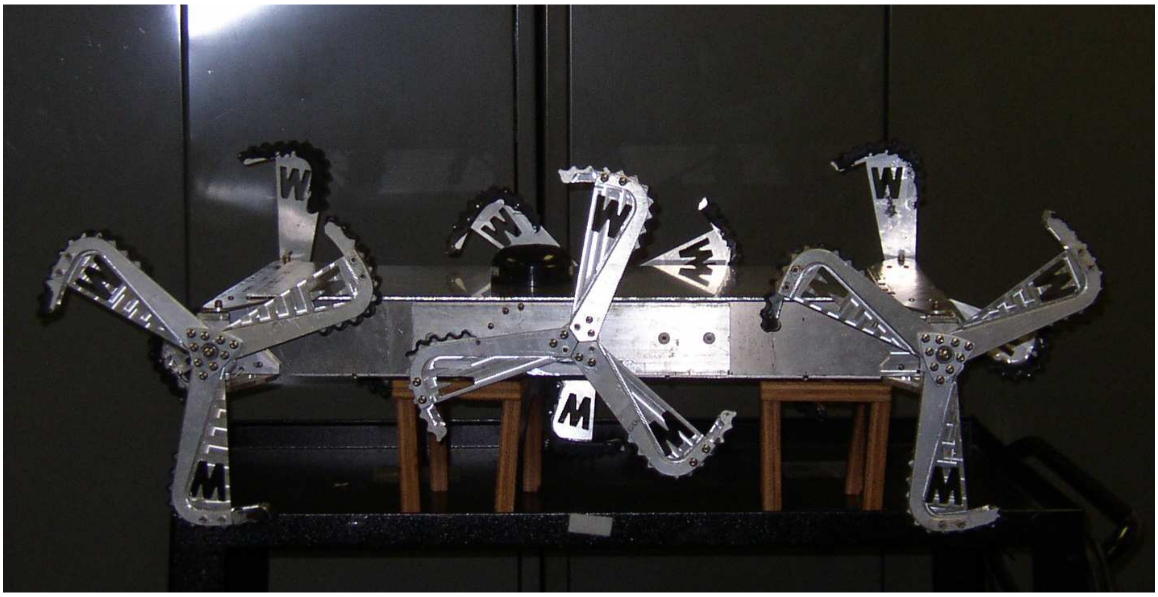

Figure 4. Agbot.

B. WHEGS^{TM}MOBILITY CONCEPT

Operating in a surf zone is difficult because of the extreme terrain encountered. The robot must be able to navigate through loose sand and traverse obstacles such as rocks or man made obstructions. Wheeled and tracked vehicles are efficient at covering terrain quickly and are simple to design and maintain. However, they lack good terrain adaptability and cannot easily overcome a large obstacle.

Other forms of locomotion such as legs, while less efficient than wheels or tracks, are excellent at adaptability and overcoming obstacles. Yet, current technology is not sufficiently advanced to the point where legged vehicles can easily be implemented.

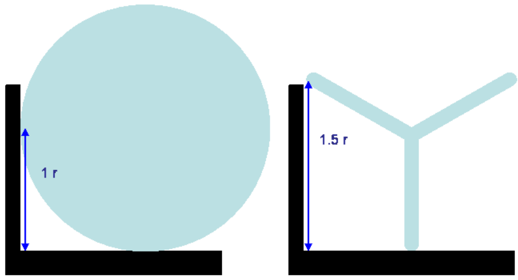

Figure 5. Comparison of the climbing abilities of wheels versus Whegs. Figure is drawn to scale.

The patented Whegs^{TM}(wheel-legs) system is used to gain the advantages of both types of locomotion. This system provides the efficiency of wheeled vehicles with some of the mobility of legged platforms [Ref. 10]. Whegs can overcome obstacles which are greater than the radius of the wheel, while wheeled vehicles are limited by this fundamental constraint, see Figure 5.

1. Biologically Based Gait

The gait which most efficiently uses the advantages of the Whegs is the tripod gait used by cockroaches and other hexapods [Ref. 1]. In the tripod gait, the two outside legs on one side and the middle leg on the other side move synchronously. Three legs remain on the ground while the other three move forward (See Figure 6). By setting the two outside Whegs on one side and the middle Wheg on the other 60° out of phase with the other three Whegs, the robot naturally uses a tripod gait. Because three legs or Whegs are in contact with the ground at all times, the platform is both statically and dynamically stable.

When a cockroach encounters an obstacle, it changes gait and all six legs are engaged to give the cockroach the extra force necessary to overcome the obstacle (see Figure 7). In addition, the cockroach has a body joint which aids in its ability to overcome large obstacles(See Figure 8) [Ref. 1].

The Whegs system mimics this gait change of the cockroach to increase mobility of the system. When the vehicle encounters an obstacle, all six Whegs can be engaged to give it the necessary extra torque to propel the vehicle over the obstacle

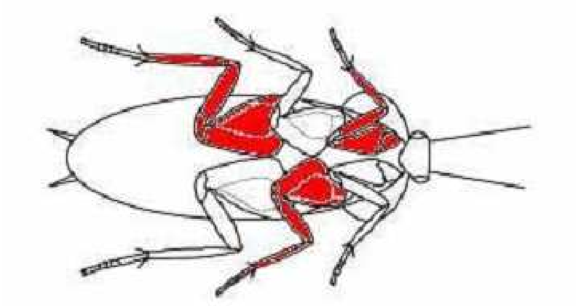

Figure 6. Diagram depicting the tripod gate on a typical cockroach (From [Ref. 6]).

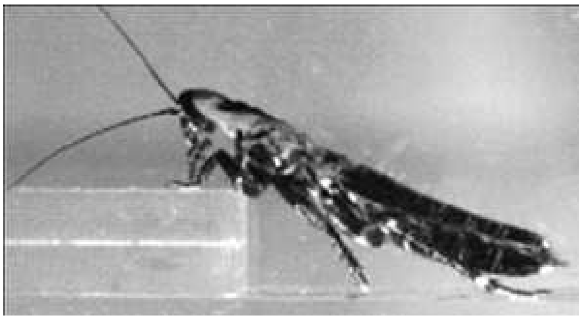

Figure 7. A cockroach changing gait to climb an obstacle (From [Ref. 14]). Notice how all legs are currently engaged to give the cockroach the extra force necessary to overcome the obstacle.

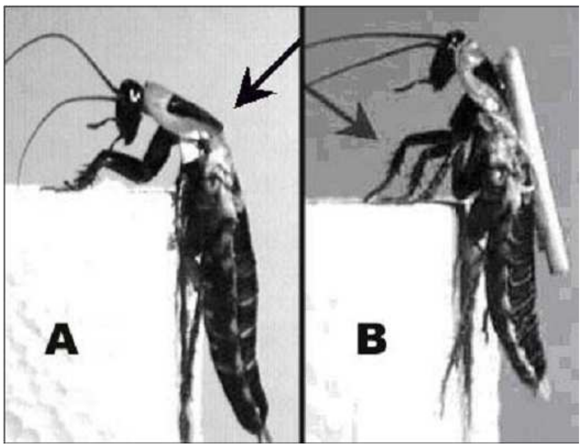

Figure 8. A cockroach shown climbing with (A) and without (B) the use of its body joint (From [Ref. 14]).

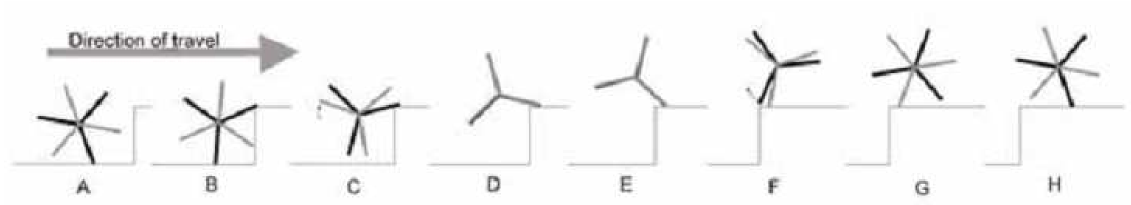

Figure 9. Diagram depicting the gait change as the Whegs encounter an obstacle (From [Ref. 6]). (A) The robot is in its normal tripod gait, (B) the Whegs encounter an obstacle, (C) the compliance devices engage and the unengaged Whegs rotate through 60° (D) and (E) all six Whegs help propel the robot up and over the obstacle, (F),(G),(H) the Whegs return to their normal phase and the tripod gait is resumed.

(see Figure 9). The gait change is accomplished by a limited slip differential which engages when a Wheg cannot move either because it is stuck or has encountered an obstacle. When this occurs, the other set of three Whegs rotate through 60° so that all six Whegs are moving in phase and the maximum amount of torque is available for propulsion. After the obstacle is cleared, the spring in the differential pulls the Whegs back out of phase and the normal tripod gait is resumed.

2. Limited Slip Differential

The limited slip differential (see Figure 10) is a completely passive mechanical element so they require no programming or electronics for control . The differential consists of two co-axial axles connected by a spring. One of the axles is connected to the Wheg while the other is connected to the drive train. In normal operation, the spring is not tensioned and the axles rotate together. Should the Wheg become stuck or encounter an obstacle, the motor will continue to turn, tensioning the spring until a mechanical stop limits further tensioning. At this point, all six Whegs will be in phase providing the extra torque necessary for enhanced mobility. In addition to allowing all six Whegs to be in phase, the tension in each spring provides approximately 34.4 N of force. This force times the wheel radius of 18.4 cm adds 6.32 Nm of torque at each Wheg.

It should be emphasized, that the differential is a completely passive device. When extra torque is needed, the differentials mechanically responses to the environment and provides the necessary extra torque. This greatly reduces the amount of programming, sensors and onboard intelligence necessary for the robot. This relieves

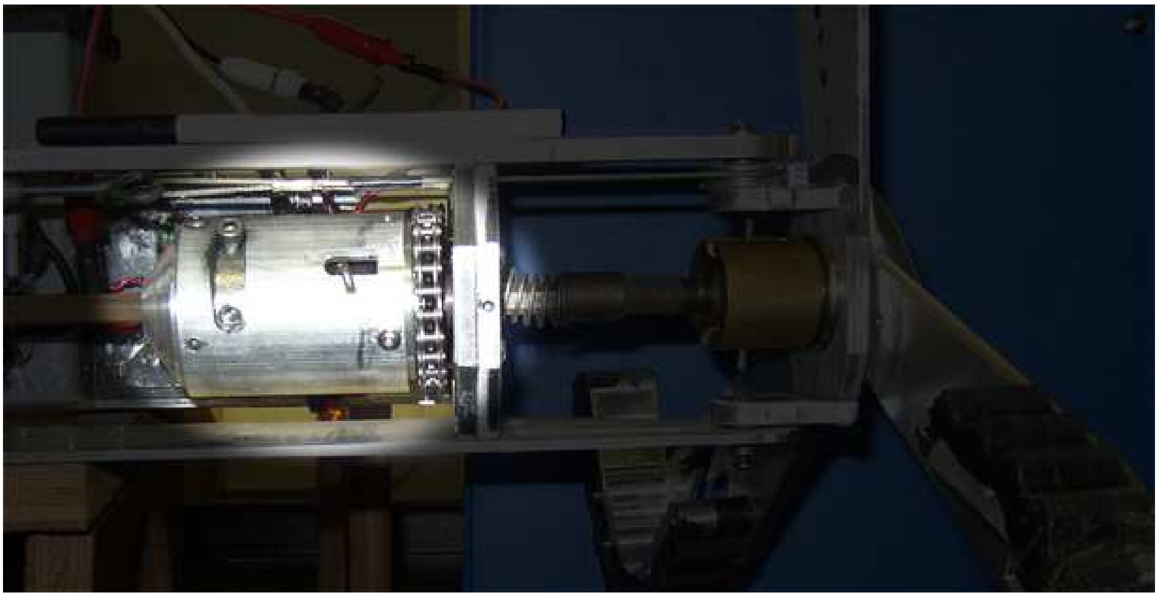

Figure 10. The limited slip differential device.

the robot of the tasks of detecting, evaluating and responding to obstacles, all of which are difficult and resource intensive processes for autonomous vehicles.

Currently, Agbot does not have a body joint like the cockroach. One was originally planned but never implemented. The body is broken up into two section which are free to rotate with respect to each other. In order to create a solid body, the two sections were locked together which caused several problems see Chapter II Section 1. Research is on–going to create a body joint which is actuated and also compliant [Ref. 3].

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II. ROBOT COMPONENTS AND CONTROL

A. OVERVIEW OF HARDWARE

Agbot has several systems onboard which enable it to autonomously navigate and control the motors and servos. The ‘brain’ of the Agbot robot is the BL2000 rabbit micro-processor (see Figure 11). The BL2000 is an embedded system which contains, among others, 256K of memory, a central processing unit running at 22.1 MHz, 10 digital and 2 analog output ports. The memory is a small amount of flash-ROM which allows a user to write and store executable programs. The I/O ports are used to interface with the other equipment on the robot.

The BL2000 gathers data from the compass, Global Positioning System (GPS), accelerometers (Subsection 6) and the wireless interface (Subsection 5) and then processes and interprets the data according to the student written program stored in the flash–ROM (Section B). Based on the operating parameters and the data gathered, the BL2000 sets the appropriate voltages on the analog–out ports. These voltages ultimately control the steering servos (Subsection 2) and the main motor (Subsection 3). The BL2000 also sends some of the data such as its position, heading and status across the wireless network to a laptop which displays the information for the user (Subsection 3).

Agbot consists partly of commercial off–the–shelf (COTS) technology originally developed for radio controlled cars. This allows easy interchange of parts should one become damaged. However, because we want Agbot to be autonomous, the control systems must be tuned to mimic a radio controller in order to interface with the

Figure 11. The BL2000 rabbit micro-processor (From [Ref. 15]).

COTS products (see Subsections 2 and 3).

The rest of this chapter focuses on individual components of Agbot and the improvements made to these systems. A more in-depth review of some of the components and specifications can be found in [Ref. 13].

1. Body Construction

The body and most of the mechanical systems of Agbot were built by Richard Bachmann of Case Western Reserve University. The chassis and Whegs are made of milled aluminum. The body comes in two sections which can rotate with respect to each other so that a body joint could be integrated at a later date. Originally, the top and bottom plates of the robot were very thin aluminum and did not cover the entire exterior. This was done in order to conserve weight on the vehicle to improve speed. Since no compliant body joint was on the robot, the body was locked with two small aluminum bars and screws.

Locking the body joint with two small aluminum bars proved insufficient because of the large amount of vibration inherent to Agbot. Whegs based platforms naturally vibrate a great deal because of the spoked nature of the Whegs. The Whegs move from two spokes on the ground to a single spokes on the ground in normal motion, see Figure 12. A three spoked Wheg system has a vertical translation of about 13% of the wheel radius during each step [Ref. 10]. This up and down motion causes large amplitude, low frequency vibrations.

Many times during trial runs, the vibrations would shake a bolt loose. Because of the natural flex point of the body joint, the two aluminum bars often failed. Instead, extra pieces of aluminum were bolted directly onto to the chassis which were much thicker and longer than the original bars. Additionally, thicker, solid, top and bottom plates were screwed onto the body to add extra stiffening of the platform. These solid top and bottom plates also helped seal the robot from sand and soil. These measures, while somewhat drastic, successfully stiffened the body to the point where the vibrations encountered were not detrimentally effecting the operation of the robot.

2. Steering Mechanism Control

The front and back sets of Whegs can turn and are each controlled by a servo, while the middle set of Whegs are fixed. The front and back Whegs turn in opposition

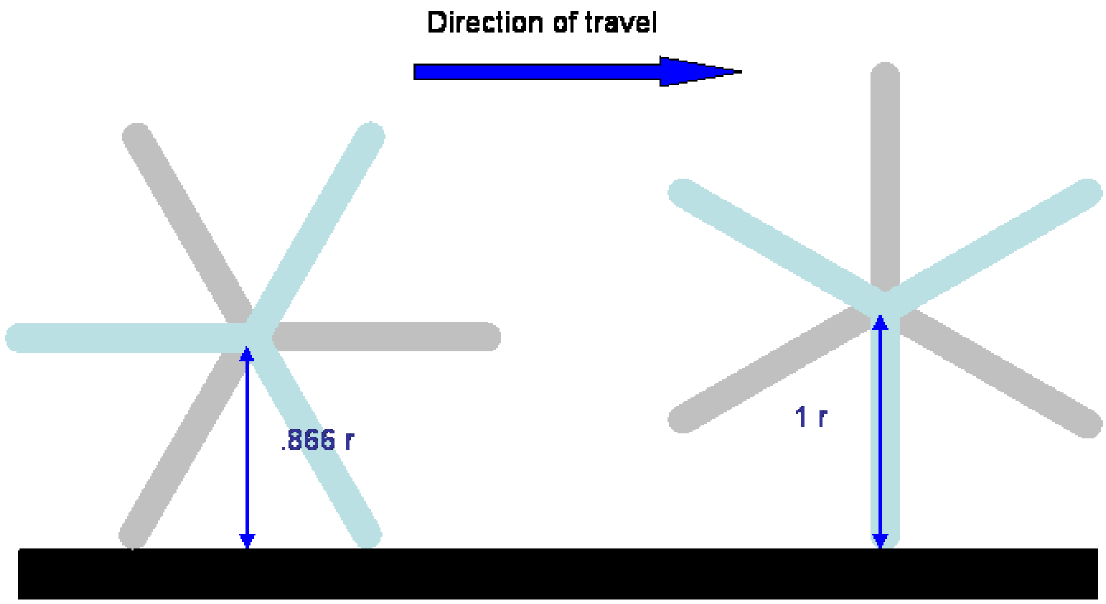

Figure 12. A diagram depicting the vertical motion inherent in the Whegs architecture. Figure is drawn to scale.

(see Figure 13) which creates a turning radius of only 5 feet ($\approx$ 1.875 body lengths). For simplicity, both servos are controlled by the same electrical signal. However, the back servo is mounted opposite the front so that the servos turn in opposition when given the same control signal (see Figure 14). The servos are connected to the Whegs by a wire cable which is looped around the servo drive shaft.

The servos chosen for the steering mechanism are Hi-tec® HG–5995TG robot servos. These servos are used because of the high amount of torque (2.4Nm) they are able to produce in a small package and have low power consumption (see Appendix A). Additionally, the servos use a titanium gear train for high accuracy and longevity. Servos are an excellent device for steering because they are robust to disturbances. If a Wheg is perturbed the servos will try to return to the desired steering angle.

Commanding these servos is a difficult task. Pulses of power are sent to the servo and these pulses determine what angle the servo turns to. The length of time the servos are sent power (a.k.a. pulse width) is proportional to the servo angle. The servos have a refresh rate of 50Hz which equates to 20ms. Thus, only one command pulse can be sent every 20ms. A pulse of 1.5ms commands the servo to center; while .9ms to 2.1ms are full right and full left respectively. In addition, the pulse

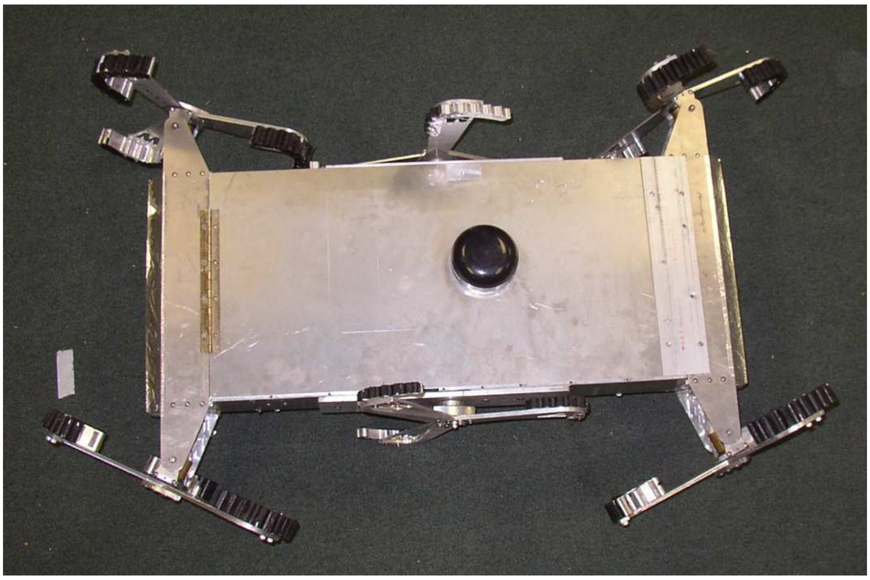

Figure 13. Agbot executing a turn.

Figure 14. The front and back servos are mounted opposite of each other so that they turn in opposition when given the same control signal. Notice the direction of the wire about the front servo (left) as compared to that of the back (right).

of power needs to be between 3 and 4 Volts. These are factory specifications which unfortunately can't be changed. They were designed to interface with a radio control receiver and not a BL2000.

However, because of the mechanical design of the steering mechanism the servo does not swing through its full angular range of 180° when executing a full turn. The pulse length only needs to range between $\approx 1.5 \pm .25ms$ for the servo to move the Whegs through their entire turning range of 50°.

The analog output ports on the BL2000 are controlled via a 12 bit digital to analog converter chip and have a 0 to 4 Volt range. This provides an analog resolution of $\frac{(4-0)}{2^{12}} \approx .001$ Volts. However in the implementation, because of load noise, a resolution of only .01 Volts is available.

Given these tight design specifications, a Pulse Width Modulator (PWM) circuit was determined to be the best avenue of approach to meet the specifications for controlling the servos.

A (PWM) circuit was used on the Lopez prototype. However, the old PWM could not achieve a pulse length of $1.5ms$ and did not truly have a cycle time of $20ms$. The old PWM board used two LM555 chips, one as a free oscillator providing a trigger signal at the desired frequency and the other chip modulating the pulse width. This design cannot provide true 0–100% modulation of duty cycle and thus could not produce the required pulse widths for control of the servos.

A different circuit design was needed to control the servos. The design chosen is a PWM using one LM555 chip producing a sawtooth wave and an operational amplifier configured as a comparator (see Figure 15). The pulse length of this circuit is changed by changing the voltage on the negative terminal of the comparator [Ref. 9].

The repetition frequency of this PWM is determined by the frequency of the sawtooth wave. This frequency is determined by the following formula [Ref. 8].

$$F = \frac{1}{T} = \frac{R_2 V_{\mathrm{CC}} - .6(R_2 + R_3)}{\frac{2}{3} V_{\mathrm{CC}} R_1 (R_2 + R_3) C_1} \tag{II.1}$$

However, it became apparent in testing that this formula is only approximate when working at low frequencies such as 50Hz. Through experimentation, a new value of

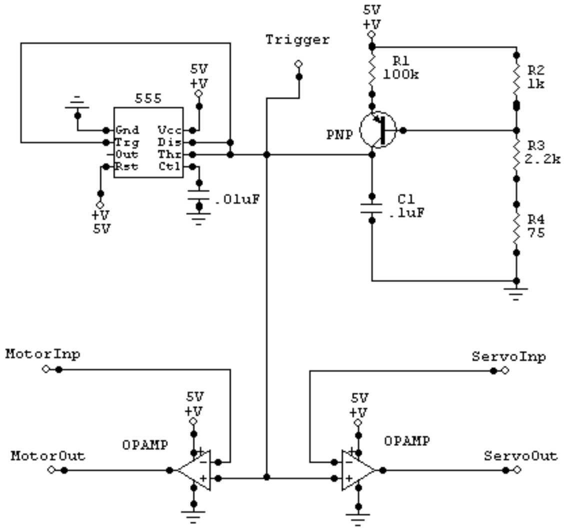

Figure 15. Circuit diagram of the pulse width modulator.

R_1 was selected and a correction resistor, R_4, was added to R_3 to produce a sawtooth wave at *exactly* 50Hz (see Figure 16).

When a comparator's positive terminal is greater than the negative it switches on and output is set to $\approx .75V_{\text{Hi}}$. Otherwise the comparator's output is set to V_{Lo}. By setting the voltage of the negative terminal on the comparator somewhere between the extremes of the sawtooth wave's voltage, the comparator can be induced to form a pulse of any duty cycle. In this case $V_{\text{Hi}} = 5V$ and V_{Lo} is tied to ground. The sawtooth wave is connected to the positive terminal of the comparator and the analog–out port of the BL2000 is wired to the negative terminal. Thus, by varying the voltage on the BL2000, a 3.75V pulse with a duty cycle anywhere between 0 to 100% can be created. This pulse signal meets all of the design requirements. Figure 16 shows the sawtooth waveform and the PWM signal sent to the servo. The control voltage from the Rabbit Microprocessor is set at 3 Volts. The control voltages used for steering varies between 3.23 V for full left to 3.27 V for full right with 3.25 V centering the Whegs.

3. Main Motor

Agbot has one motor which drives all the Whegs through a chain system. Because this motor must propel the entire robot, it must deliver high torque while also being efficient or the batteries will be drained too quickly.

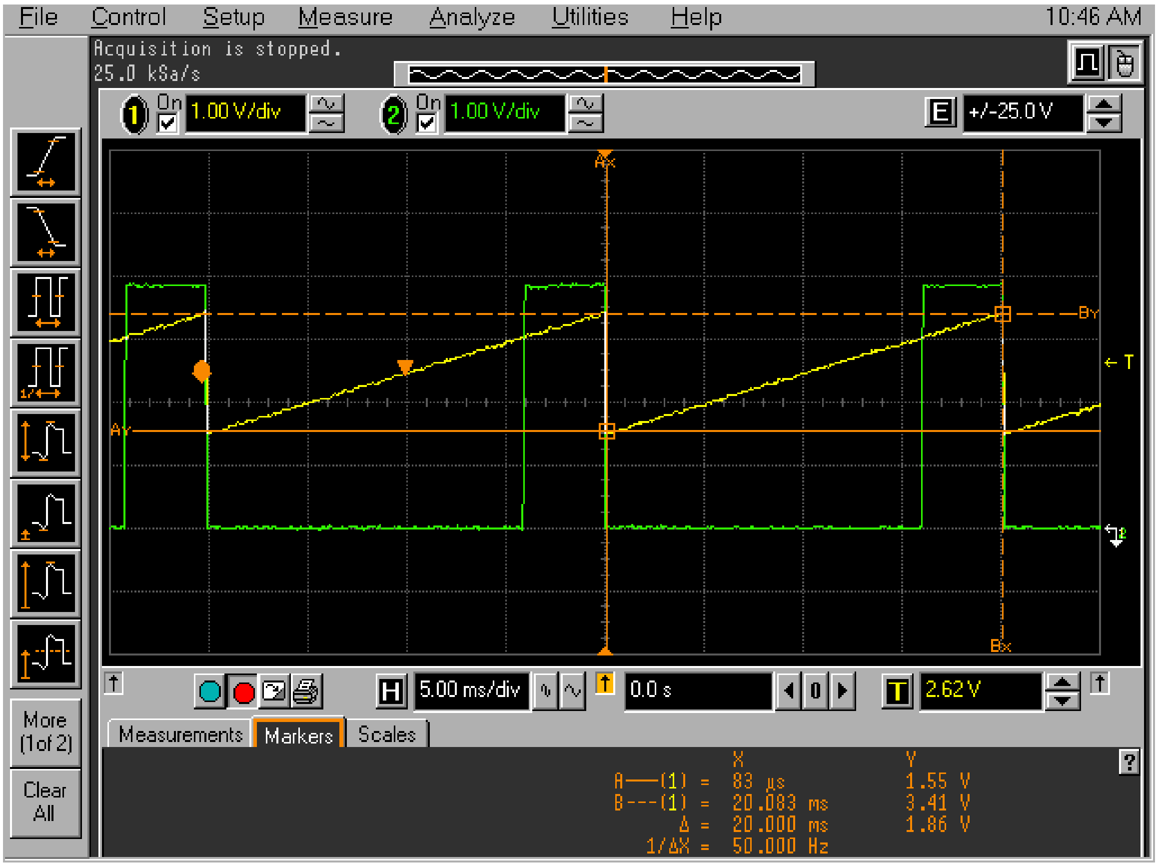

Figure 16. The waveforms created by the PWM. The control voltage is set at 3 Volts. The yellow waveform is the linear ramp created by the LM555 while the green waveform is the output to the servos or motor controller. The other markers are used to measure the waveforms and give the frequencies and voltages displayed at the bottom of the screen.

The motor selected for this task was the Maxon© RE 40 148866 series motor with the GP 42C 203123 planetary gearhead. This motor has 98.7mNm of continuous torque and provides 150W of power. The gearhead provides a gear reduction ratio of 74 : 1. The motor previously used in Agbot only had a gear reduction of 43 : 1. Appendix B contains the technical details of the motor and gearhead.The higher gear ratio improves the robot's ability to climb obstacle but reduces its speed. Over hard sand, it was observed to move at a speed between 1 and 4 mph. However, the speed significantly increased when in softer sand and also over grass. Even with the lower gear ratio motor, Agbot was still able to climb stairs.

The motor is controlled in much the same fashion as the steering except it has an electronic speed controller which regulates the power to the motor. To control the motor an analog voltage is set on one of the analog–out ports of the BL2000. This

Table I. Power Bus battery specifications.

Battery	Nominal Voltage (V)	Capacity (mAh)	Chemistry
Motor	14.0	6600	Ni-MH
Electronics	11.1	2480	Li–ion
Servo	6.0	700	NiCd

voltages changes the pulse width using much of the same circuitry as the steering but with a different comparator (see Figure 15). For Agbot we are using Team Novack's® Super Rooster©. This ESC was originally designed for RC race–cars and so the PWM signal mimics a the signal which would be generated by a RC receiver. An ESC is necessary to control the motor because the large current needs of a motor cannot be sourced through the sensitive electronics of the PWM. The ESC acts as a gateway through which large amounts of current can safely pass.

4. Batteries and Electrical Distribution

The electrical system was not standardized and had several shorts and broken leads. A large amount of time was spent, troubleshooting, cleaning and re-wiring the electrical system. The system is standardized with three sets of power distribution wires for Agbot. The first is a small 700mAh Nickel–Cadmium battery which powers the servos. The second set is the motor batteries which are only separated from the motor's ESC by a switch. Finally, there is the electronic's batteries which includes a voltage regulator to supply voltage to the PWM board (see Subsection 2).

For the electronics, a lithium-ion (Li–ion) chemistry battery was selected because of its high capacity, light weight and ability to provide the same voltage throughout its discharge cycle. The battery used is an Apogee 2480mAh 11.1V battery.

For the motor bus, a pair of Nickel Metal Hydride (Ni-MH) batteries are used in series. Each battery has a capacity of 3.3Ah and provides between 8.4V fully charged and 5.4V at full discharge. Wiring the batteries in series creates between 16.8 and 10.8 V for the motor and the large capacity provides plenty of current.

5. Communications Equipment

The BL2000 has an RJ-45 jack so it can connect to a standard ethernet cable, this then allows wireless transmission of data back to a computer. Previously, Agbot used Proxim© wireless modems to communicate to a base station laptop. Currently, Agbot has been upgraded with a wireless ethernet router. This allows the base station laptop which has a wireless ethernet (802.11G) card to connect directly with the BL2000 rather than going through a wireless modem. Upgrading to the router allows easy interface with up to 3 additional ethernet enabled components. For instance, Bender had an ethernet camera which allowed it to send video back across the wireless link. Using the wireless modems, Agbot did not have this capability.

6. Navigation Components

The most important piece of navigation equipment is the global positioning system (GPS). Agbot uses a Garmin© maritime GPS. The GPS sends a standardized encoded string of characters which includes the number of satellites it is receiving from, the type of fix and the current position. This string is received by the BL2000 and interpreted to extract the current position of the robot.

In North America the GPS signal can be augmented by a Wide Area Augmentation System (WAAS). The WAAS system consists of 25 ground reference stations, two master ground stations and two geo-stationary satellites. The 25 ground stations receive GPS signals and calculate errors in the signal caused by, among other things, atmospheric delays, orbital errors and clock drift. These errors are collected by the master ground stations and location specific error corrections are calculated and uploaded to the WAAS satellites. These satellites then broadcast the error reports so that a mobile GPS receiver can apply the appropriate corrections to its signal. When receiving a WAAS signal, the GPS position can be accurate to within less than three meters [Ref. 5]. The error reports are uploaded every two minutes but the reports are considered valid for up to 6 minutes. Thus, a mobile GPS receiver does not need to receive every single report to maintain its WAAS corrected position. Receiving a WAAS signal does not require extra equipment or antennas like differential GPS does.

Agbot also has a Honeywell HMR3000 digital magnetic compass. This compass, besides reporting heading, also determines the pitch and roll of the robot. It should be noted that Agbot steers by magnetic heading only. A geographic north is not required because Agbot calculates its next course based on *relative* bearings, not based on true bearings.

If a GPS signal is not available, for instance, if the robot is underwater, the robot still needs to navigate towards its destination. Thus Agbot is also equipped with a three axis accelerometer. The accelerometer allows for dead reckoning by integrating the acceleration over time twice to get position. This technique gives a good approximation of the position. Once during testing, Agbot defaulted to dead reckoning, however, this component has not been quantitatively tested to determine how accurately it can determine the robot's position.

B. PROGRAMMING AND CONTROL

Agbot has a user written program stored on the BL2000 which interpreters the navigation data and controls the platform. If the program is in manual control mode, then the program merely reports the data back to the user and waits for control commands from the user (See Section A.3 for how this is accomplished). When the robot is navigating autonomously, five processes are executed cooperatively using co–statements. Co–statements are a built-in feature of the Dynamic C programming language which is the native dialect of the BL2000. Co–statements allow the processor to multitask by devoting processor time to a co–statement until certain parameters of the co–statement have been met at which point it checks the other co–statements to see if their parameters have been met. Each of the co–statements needed for autonomous navigation have a few lines of code at the beginning which determine if it is necessary to execute the rest lines of code in the co–statement. The BL2000 will continue to check each of the co–statements until it is shut off.

For autonomous navigation, there are five main co–statements which are executed cooperatively:

- GPS
- compass
- dead reckoning
- waypoint processing
- navigation

The GPS co–statement gathers the current position from the GPS and passes this position information to the waypoint processing and navigation co-statements and also passes this information to the user. The compass co–statement is similiar to the GPS co–statement except that it gathers heading, roll and pitch information from the compass. The Dead Reckoning co–statement is only invoked if there is no GPS signal at which point it uses information from the accelerometers to give an approximate position. Finally, the waypoint processing co–statement determines if Agbot is at the next waypoint and passes stored waypoint information to the navigation co–statement. The navigation co–statement gathers the current position, heading and next user defined waypoint and determines a course to the next waypoint.

Two other co–statements are running whether the robot is in autonomous or manual control. The first is the manual control co–statement. This co–statement listens to the wireless connection to determine if the user wants to take control of the robot. Once in manual control, the GPS and compass co–statements still run and pass information to the user, but the navigation co–statement no longer determines the course and speed; the user now has control of these settings. The other co–statement that is always running is the control co–statement which translates the desired course and speed into motor and servo control voltages. Figure 17 details the control flow of the Dynamic C program. [Ref. 13] gives a more detailed account of the programming and control of Agbot.

1. PID Control

In general terms, a PID controller is invoked in a closed loop feedback system for our robot in order to control the platform's heading while proceeding to a way-point. Figure 18 shows how a reference step function "r" is added to desired output "y" to produce an error signal "$e(t)$". This is operated on by the PID controller in

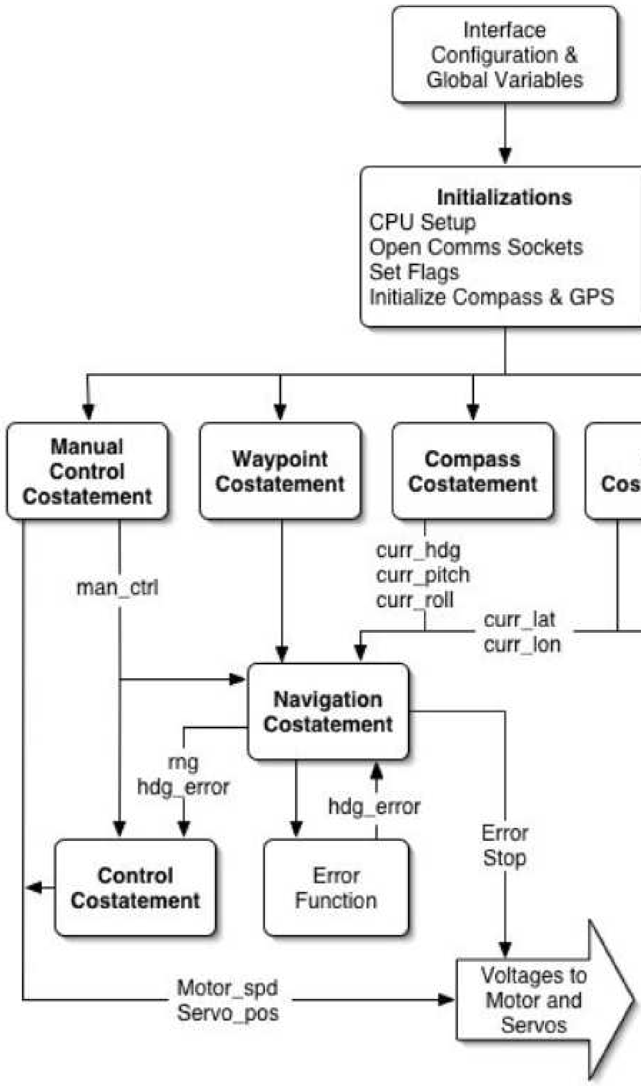

Figure 17. A flow chart of the Dynamic C program (From [Ref. 13]).

a theoretical system. The output of the PID controller is the control signal "$u(t)$". This is sent to the plant which signals the platform to respond in such a way that the error is driven to zero in a critically damped way.

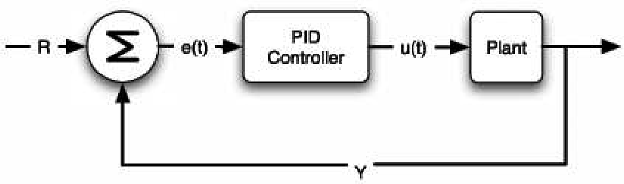

Figure 18. The PID Control Loop.

The time domain PID control equation is given by:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{d_e(t)}{dt}\right) \tag{II.2}$$

In this case $u(t)$ is the time dependent control signal, K is the proportional gain, the integral time is T_i and T_d is derivative time. For our robotic system we have implemented our PID controller via a compensator in the control code, see figure 19.

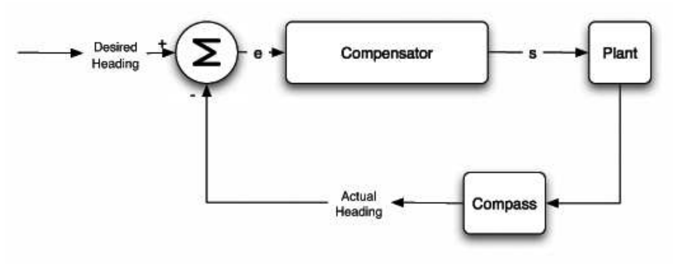

Figure 19. Robot PID architecture.

It is straightforward to invoke PID control via a hardware compensator with a combination of operational amplifiers, as shown in figure 20.

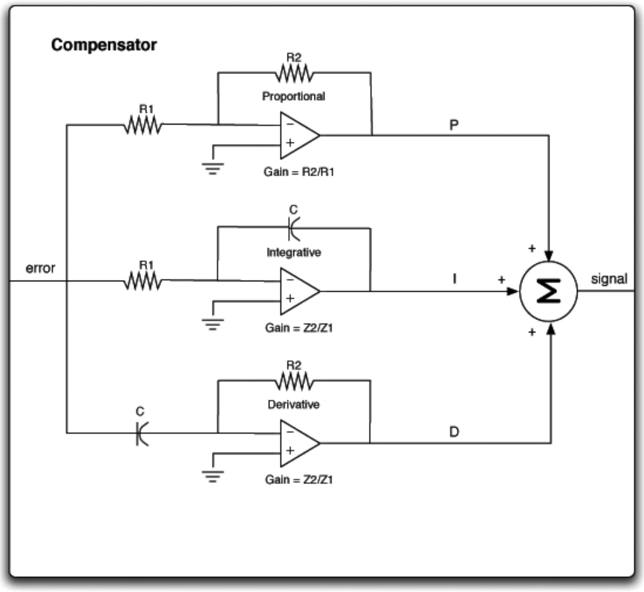

Figure 20. A hardware compensator to actualize a PID controller.

Our time domain control signal equation is then rewritten as follows:

$$s(t) = P + I + D \tag{II.3}$$

where $P = \left(\frac{R2}{R1}\right)e(t)$, $I = \left(\frac{Z2}{Z1}\right)e(t)$ and $D = \left(\frac{Z2}{Z1}\right)e(t)$ and we understand that the impedance ratios are simply the gain of the specific operational amplifiers P, I and D. So our control signal is then the algebraic sum of the proportional, integrative and derivative signals coming out of each operational amplifier. If we let $G_P = \frac{R2}{R1}$, $G_I = \frac{Z2}{Z1}$ and $G_D = \frac{Z2}{Z1}$ then this can be more formally written as:

$$s(t) = G_P e(t) + G_I \int_0^t e(\tau)d\tau + G_D \frac{de(t)}{dt} \tag{II.4}$$

In practice, it is easier to manipulate and tune the PID controller if we invoke the compensator in software. To do this we must take into account sample rates and code loop delays and how they apply to our control signal. This is better understood as we rewrite our equation in such a way that it is easily translated to code:

$$s(i) = G_P e(i) + G_I \sum_{i=0}^{N} e(i) + G_D[e(i) - e(i-1)] \tag{II.5}$$

From the above we see that we simply need to calculate and store the error $e(i)$ and properly set the the gain coefficients for our PID controller.

2. PID Tuning

To tune the response of our system to error inputs, we need to identify the important parameters to planned and unplanned disturbances. With that information, we are then able to properly set the PID gain coefficients for this tuned response.

For example, we want the robot to respond properly when a command is sent to move to a different heading and proceed to the next way point. We also want the platform to return to a steady and stable state if it is moved by unexpected external forces. Finally the system should to be immune to environmental noise.

The parameters we are interested in can be obtained by observing the time domain system response to a step function.

- The Rise time
- Overshoot
- Settling time
- Steady State Error

In an effort to minimize these parameters, an adaptation of the Ziegler-Nichols Method is proposed:

Table II. Ziegler-Nichols Table.

Control	K	T_I	T_d
P	$\frac{K_c}{2}$		
PI	$\frac{K_c}{2.2}$	$\frac{P_c}{1.2}$	
PID	$\frac{K_c}{1.7}$	$\frac{P_c}{2}$	$\frac{P_c}{8}$

Here K_c is the critical gain and is determined by putting the I and D gain coefficients to zero and increasing the P gain until the system goes into a steady state oscillation in response to a step function. The period of this oscillation is measured, and we call this the critical period P_c. With this we determine K, T_I and T_D from the table. We then can map these into our definition for gain coefficients as follows:

$$G_P = K \tag{II.6}$$

$$G_I = \frac{G_P}{T_I} = \frac{K}{T_I} = \frac{K \times 1.2}{P_c} \tag{II.7}$$

$$G_D = \frac{G_P}{T_D} = \frac{K}{T_D} = \frac{K \times 8}{P_c} \tag{II.8}$$

For example, let us assume that at a K_c of 2, P_c was observed to be 2 seconds. Then $G_P = 1.2$, $G_I = 0.72$ and $G_D = 4.8$.

In addition to the above there are some general rules of thumb that can be employed to help tune robot system response. Table III gives us some insight on how the different types of control effect the outcome of the system response to a step function. From this table we notice that although our desire is to minimize all of the observable parameters, it is not possible to do so. We often optimize one parameter at the expense of another.

Table III. Control Response Effects.

Control Response	**Rise Time**	**Settling Time**	**Overshoot**	**Steady State Error**
Proportional	Decreases	No Effect	Increases	Decreases
Integrative	Decreases	Increases	Increases	Eliminates
Derivative	No Effect	Decreases	Decreases	No Effect

3. Java Graphical User Interface

A Java© based Graphical User Interface (GUI) was written by Kubilay Uzun for the Bender prototype. The program was modified slightly so that it could interface with Agbot. The program allows the user to define waypoints and control the robot using a GUI. The program also gathers position and bearing data and displays this for the user. One modification done in finalizing the Agbot prototype for testing was to remove the calculations of voltages from the program. Previously, speeds and directions were set by the user and then the Java program calculated the motor and servo control voltages and sent these across the wireless network. However, in finalization, the control voltages were changed many times and so this aspect was

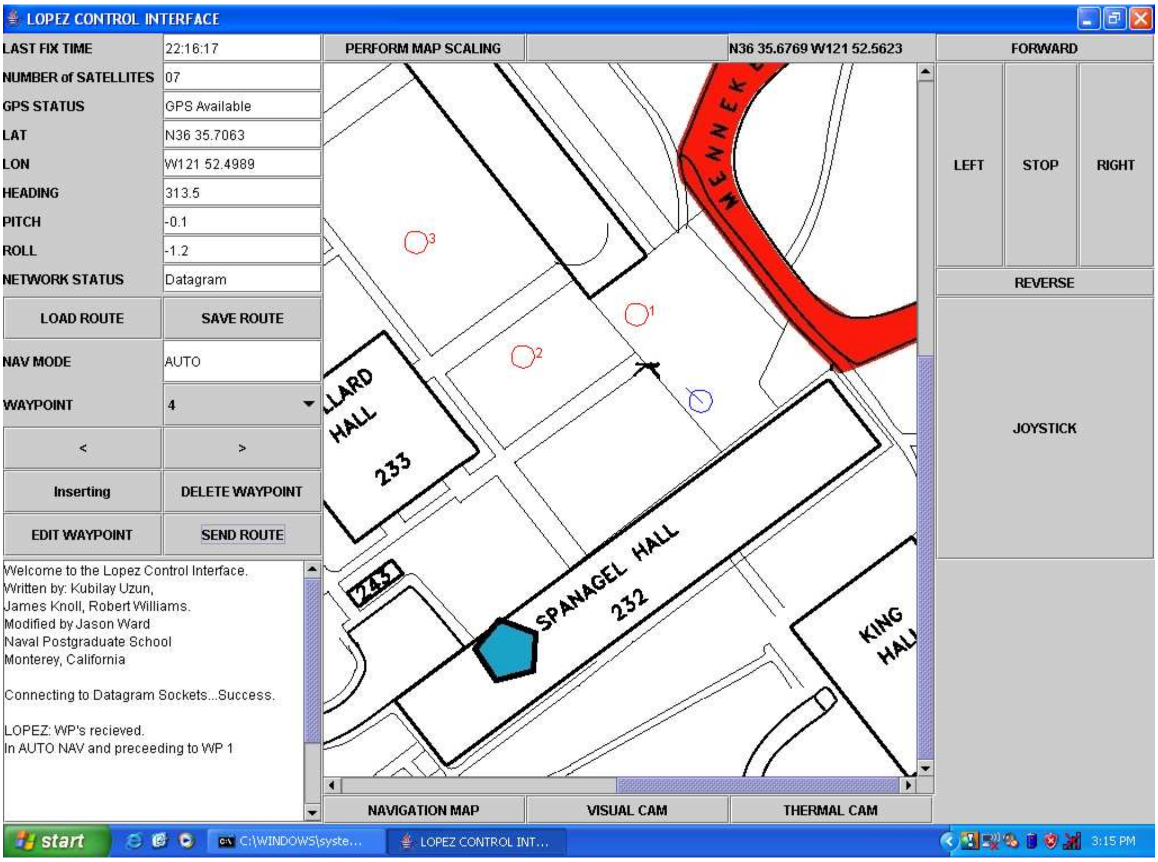

Figure 21. The Java based GUI.

removed from the Java program. Instead, the Java program only sends the codified speed and directions to the BL2000. Speed can range anywhere between -50 to 50 with 0 being stop. Left and right vary in the same manner. The BL2000 then interprets these codified speeds and directions and sets the motor and servo voltages accordingly. Doing this allows the hardware to be modified to any type of servos and/or motor without having to modify the Java GUI code. Now, only the Dynamic C code needs to be updated when new hardware is installed. The Java GUI is now a more universal interface and other robotic projects in the SMART initiative are using the GUI. See Figure 21 for a screenshot of the GUI.

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III. TESTING AND RESULTS

A. RESULTS OF AUTONOMOUS NAVIGATION ON GRASS

We had several successful and partially successful tests of the autonomous behavior when testing Agbot on the grass. The robot successfully communicated with the laptop GUI interface and reported its position during several runs.

The robot turned towards the waypoints and navigated towards them, even when it became slightly off course. The steering mechanism and axle joints have become loose over time and the hard steel has deformed the softer aluminum and brass. This meant that often the robot would hit a divot or rock and the steering was loose enough so that the Whegs were pushed out of position. The control system, however compensated for these perturbations and navigated the robot back onto course. This demonstrates the adaptability of the control system and that minor course changes were not detrimental to the operation of the robot.

The locomotive elements of the robot were demonstrated to work correctly also. The motor was successfully controlled and it slowed as the robot approached the waypoint so that the robot would not overshoot. However, the reduced speed caused some steady state error as the robot approached its final waypoint. Yet this steady state error can easily be compensated for by changing the integral term on the PID controller to a non–zero value as discussed in Chapter II Section B.18.

The limited slip differentials also engaged several times throughout the run. It is difficult to determine how many times the differentials were engaged, but it is clear from observation that several times throughout the run the Whegs rotated into phase to provide extra torque. Because of the deformation of the brass socket on the ball and socket joint, the Whegs are not always completely 60° out of phase. This problem reduces the effectiveness of the differentials and the efficiency of the Whegs. Therefore, it appeared that the differentials were being engaged simply to aid in the forward motion of the robot.

During the runs on the grass, there was a considerable amount of vibration. The grass and soil did little to damp the impact of the Wheg as it struck the ground and so several runs were cut short by mechanical problems caused by the vibration.

Some of the runs were only partially successful because of GPS errors. The grass runs were done on the NPS campus quad. This reduced the space available and so our waypoints had to be set close together. The distance between the waypoints was approaching the limit of the GPS accuracy. Additionally, because of the large concrete buildings on the NPS campus, often the GPS would lose the WAAS signal which greatly reduced the accuracy of the GPS. These factors made it difficult to determine how the robot was performing. The robot acted upon its inaccurate position in order to navigate to the waypoint, and consequently missed the actual position of the waypoint, but it believed it was on target.

B. RESULTS OF AUTONOMOUS NAVIGATION ON SAND

Several of the problems encountered with the testing on the grass were not present during the testing of the robot on sand – the environment it was designed for. First, the vibrations were greatly reduced. This is likely a combination of both the improved body stiffness which was implemented for these runs and also the damping effect the sand had on the impact of the Whegs. There was still some vibration present during the runs which caused a mechanical failure on the motor mount at the end of the run.

Secondly, the GPS signal was much stronger and more accurate throughout the run. During the tests, the GPS never lost the WAAS signal so the accuracy was enhanced. Additionally, with no obstructions or buildings on the beach, a large test area could be created to test the autonomous navigation. This scenario is much closer to the eventual implementation scenario and so these advantages will be present.

During the test run, the robot navigated itself to within approximately 1 meter of each of the three waypoints. This amount of accuracy and precision exceeds requirements for marking potential mines and doing beachhead reconnaissance.

Interestingly, the robot moved faster on loose sand than on the hard, damp sand, exposed by low tide. On the hard sand, the Whegs had a tendency to slip and therefore the robot did not move very fast. The robot was observed at a speed between 1 and 4 mph. A speed test was attempted in loose sand, but due to the mechanical failure of the motor mount could not be completed. However, qualitatively, it was observed to move faster in the lose sand. It was predicted that in loose sand the robot, would ‘spin its Whegs’ and not go very far. The Whegs did bury themselves somewhat, but this seemed to give the robot more traction than on hard sand causing the robot to move faster. Perhaps a future Wheg design could incorporate a cleat like structure on the ‘feet’ to give the Wheg more traction on hard sand and increase its speed.

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IV. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

Overall, the runs on the beach were very successful as the the robot was able to navigate extremely accurately to its waypoints. The robot also demonstrated that the Whegs performed better on sand than on grass and soil which lends credence to idea of using this design for a surf zone robot. The Java GUI interface worked brilliantly and provides an easy interface for this robotic platform and other platforms. Additionally, the navigation program and equipment worked extremely well and should be kept for the next iteration of the prototype. More analysis needs to be done regarding the torque and speed requirements to determine if the one motor is adequate or needs to changed. The batteries used on the project were sufficient for the type and amount of testing done. However, these batteries most likely could not be used for an extended mission, the batteries will only last between 15 to 30 minutes depending on load. There is plenty of room for more batteries but a special industrial battery with a large energy density might be needed.

Agbot suffered from some severe mechanical shortcomings. The first is the undamped body joint which required major mechanical improvements to keep the robot from structural damage. In future Wheg designs, the body joint should either be compliant with some sort of spring and damper system to absorb shock or the body should be of solid construction. Putting a body joint in and then trying to clamp it into position leads to large mechanical stresses.

Secondly, the connection between the axle and the Whegs was insufficient for the platform torque requirements. The brass socket was too soft for the steel ball and had significant deformation. This caused the Whegs to not truly be 60° out of phase which greatly reduces the advantages of the tripod gait and limited slip differentials.

Finally, Whegs platforms have a large amount of vibration inherent to the design. The platform, while adequate for prototyping and testing, would not survive more demanding tests. Future platforms should be designed with careful consideration to the amount of vibration and shock loads which will be present on a Whegs platform.

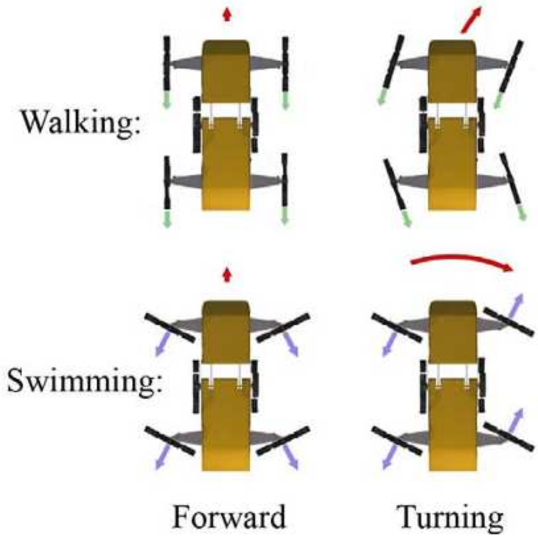

Figure 22. The steering requirements for both walking and swimming (From [Ref. 3]).

B. FUTURE WORK

1. Steering Mechanism Improvement

In order to achieve the steering requirements for both swimming and walking, the steering mechanism must be redesigned. Currently, there are only two servos, one front and one back, being controlled by a single control signal. To meet the demands of steering in water and on land, each of the four corner Whegs would need to be independently controlled and have at least a 160° range of motion(see Figure 22) [Ref. 3]. This type of mechanism would require four different servos, one for each of the corner Whegs and each servo being commanded by a different control signal.

The BL2000 only has two analog out ports, currently one is used for the motor controller and the other is used for the steering control. Thus, using an analog control voltage cannot be scaled up to four independent control signals for each of the signals. Either a new micro–controller which has more analog out ports needs to be used, or a new control scheme must be invented.

One possible control scheme would be to use the digital output ports. Some testing was done to see if the digital response was fast enough to control the servo. The digital output could not change rapidly enough to meet the design specifications. There was a significant rise time on the voltage which prevented the digital signal from reaching the needed 3 to 4 volts for the entire pulse length. In addition, the digital outputs can only supply voltage and not power and so additional electric circuits would have been necessary to supply a pulse of power to the servos. Further tests are needed to determine how the rise time effects the control of the servos. The BL2000 has 10 digital output ports so scaling up would not be a problem.

Another possible scheme is to have a digital to analog converter (DAC) connected to the digital outputs ports of the BL2000. This allows for more than one analog PWM circuit to be controlled from the BL2000.

2. Sensors and Obstacle Avoidance

Given the surf–zone environment that the robot would be working in, it would be extremely difficult to accurately map the environment and compute a pre-planned path to the objective. Additionally, part of this robot's mission is to do reconnaissance work and map a beachhead. Therefore, off-line predetermined path planning and obstacle avoidance is not an option. The robot must use real–time path planning and obstacle avoidance techniques. An active approach to path planning uses sensors and onboard intelligence to anticipate obstacles and dynamically plan a path around them. A passive approach does not anticipate obstacles and steer around them, but merely changes the robots path when the robot physically encounters an obstacle.

The Bender prototype incorporated three ultrasonic transducers which were used for active anticipatory obstacle avoidance. The SMART initiative has also suggested that future prototypes use ultrasonic sonar or other sensors for obstacle avoidance. [Ref. 13: page 41] However, there are several problems with active, anticipatory obstacle avoidance for a surf zone robot with a Whegs architecture.

The motivation for using Whegs is their high degree of mobility and ability to overcome small obstacles. Whegs can easily overcome obstacles which are greater than the radius of the Wheg (see Chapter I Section B). Thus, a sensor suite and onboard intelligence would need to accurately perceive and determine if an object can be overcome by the platform or if the platform needs to avoid the object. Sensing and accurately determining when an object needs to be avoided is an extremely difficult problem for robotics. This problem lead to a humorous incident in DARPA's 2004 Grand Challenge. An autonomous, 16 ton tactical cargo truck became stuck when it interpreted bushes as an insurmountable obstacle [Ref. 4].

Secondly, the amount of vibration observed on Whegs platforms would cause a large amount noise in a sensor system. Both Laser range finders and sonar based transducers require a stable platform to receive an accurate picture of the environment ahead of them. A vision system can be more robust to vibration, but to do so requires an enormous amount of computational power. Previous to this, no Whegs based platforms has been autonomous, or incorporated onboard sensors so no research has been done on obstacle avoidance routines or sensor integration on a Whegs platform.

Additionally, any type of sensor would need to work both underwater and on land. Finding a sensor to accomplish this would be difficult. A sonar based sensor would be difficult to use since sound propagate differently in air than it does in shallow water. The difference in propagation path would need to be taken into account and corrected for via complex algorithms. Vision systems do not work well underwater, especially with the robot disturbing the sediment and therefore reducing visibility. Alternately, different sensors could be used for each environment. However, the robot would need to know which sensor to use and possibly how to resolve conflicting sensor information. Multiple sensors systems add a degree of complexity to the robot and require greater on-board intelligence [Ref. 12].

Instead of active anticipatory obstacle avoidance, it appears that the best avenue of research for path planning through a surf zone is a more passive approach. The robot would be driving ‘blind’ but a contact sensor could be placed on its front edge so that it would know if it ran into an obstacle. If this occurred, the robot would back up, turn and try a different approach angle to its destination.

Secondly, a software obstacle avoidance routine could easily be integrated into the navigation function. The robot could monitor its position and if its position hasn’t changed after a certain amount of time, despite the robot’s efforts to move forward, the robot would assume that it has encountered an obstacle and is stuck. The robot could then back up and change its approach angle.

Passive path planning is not as efficient as an anticipatory approach. Often, a passive approach will take longer and cover more distance to reach its destination than an anticipatory approach. However, a passive approach requires much less complexity and artificial intelligence which usually reduces the probability of system failure, time and cost of development and end unit price. It should be noted that real-time path planning, either active or passive, does not guarantee a robot will reach its destination. Without global knowledge of the environment, few guarantees can be made about a robot's motion [Ref. 7].

3. Wheg Improvement

A three spoked Wheg offers a high degree of mobility. However, it also introduces considerable vibration on the platform (Chapter II Section A.1). After short test runs of Agbot, several screws and bolts had become loose, sometimes with detrimental effect. The vibrations have caused the harder steal axel to deform the softer brass cup which forms the ball and cup joint which connects the Whegs to the axle. This has caused a large amount of play in the phase of the Whegs — almost to the point where the Whegs are in phase without the use of the compliance devices. Overall, these large mechanical vibrations are degrading the performance and shorting the life of the mechanical parts of Agbot.

A possible solution to the problem of vibration is to move to a four spoke Wheg. A four spoke Wheg reduces the climbing ability of the vehicle, but not to a great degree. A three spoke Wheg with radius r can climb obstacles up to $(1 + \sin(30°))r = 1.5r$. Whereas a four spoke Wheg can climb obstacles up to $\frac{2}{\sqrt{2}}r \approx 1.41r$ (see Figure 23). A four spoke Wheg would offer a smoother ride for the robot; the vertical translation is only 8% of the Wheg radius vice the 13% on a three spoked Wheg [Ref. 1: page 28].

Another possible solution is to incorporate springs or other shock absorbers directly into the spokes of the Whegs. The vertical translation would still be present but the ride would be less jarring and hopefully not as detrimental to the robot's mechanical pieces. Research has been done into adding leg compliance in [Ref. 1: page 29].

4. Next Generation Prototype

Currently, discussions are ongoing about how to design the next generation prototype. The next prototype should be waterproof so that the amphibious capabilities of a Whegs based platform could be assessed.

Waterproofing Agbot is not a viable option because of the axle and joint construction and the numerous through–hulls in the body. Additionally, the body is

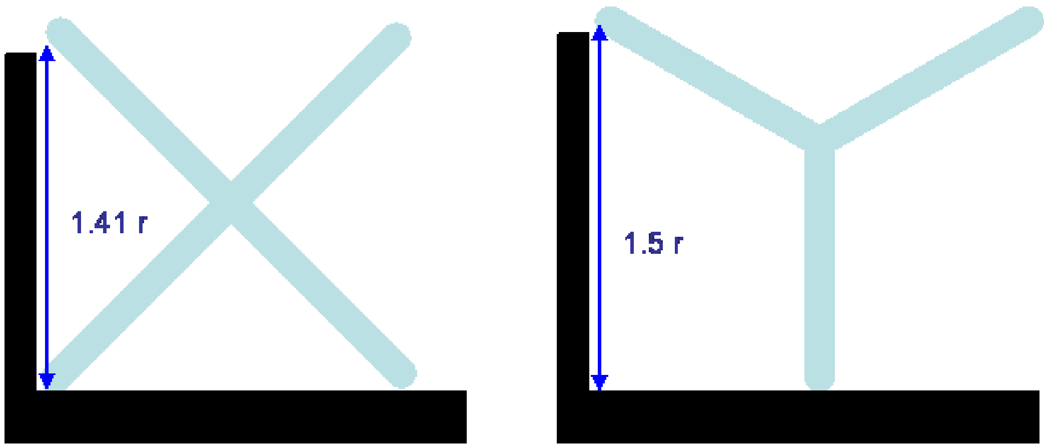

Figure 23. The climbing abilities of a four and three spoked Wheg. Figure is drawn to scale.

not in good shape because of the amount of vibration encountered during the test runs. The steel screws have deformed the softer aluminum in several places which has weakened the body considerably. Instead, a new prototype should be constructed which is fully waterproof or at least is able to house all of the electronics in a watertight container. Additionally, a different type of Wheg spoke could be used which is a cross between the current Wheg spoke and a propeller (see Figure 24). Some testing has been done on this design [Ref. 3] and the design has evolved into a "swept blade configuration." [Ref. 2]

Figure 24. A rendering of a cross between a Wheg and a propeller to be featured on the next generation prototype (From [Ref. 2]).

Plans are also being discussed regarding using composite materials for the next generation prototype. Materials like epoxy–carbon fiber and kevlar offer great strength to weight ratios and could help stiffen the body while reducing weight. However these materials do not have omnidirectional properties like most metals and so careful analysis of the stresses and loads will need to be done before going to a complete carbon fiber design.

Additionally, the ball and socket design of the joint between the axle and the Wheg should be closely examined. The joint between the axle and Whegs needs to be strong to keep the Whegs in their proper phases while at the same time, allowing the Whegs to freely spin and turn. Renderings of the next generation prototype show a crown gear system which might be stronger than the ball and socket system currently used. However, this gear system would be exposed to the elements of salt water and sand which are very detrimental to gears. Another possibility would be to use a universal joint to connect the axel to the Wheg, the difficulty would be allowing 160° of motion necessary for swimming. A constant velocity joint such as those used on front wheel drive cars are also being considered.

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APPENDIX A. SERVO SPECIFICATION SHEET

Servo specification sheet from:

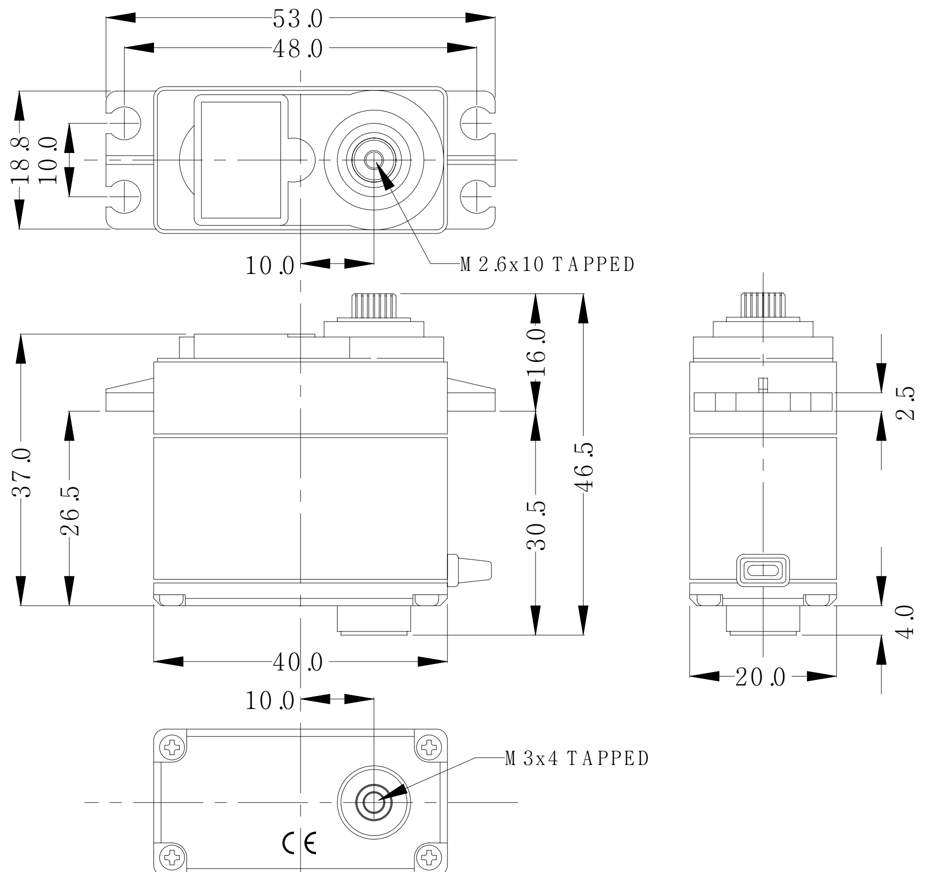
`http://www.hitecrcd.com/Servos/spec_sheets/HSR-5995TG.pdf`

PREPARED BY JUN HEE,LEE
UPDATE:JAN 01,2004

GENERAL SPECIFICATION OF HSR-5995TG CORELESS DIGITAL SERVO

1.TECHNICAL VALUE

CONTROL SYSTEM	:+PULSE WIDTH CONTROL 1500usec NEUTRAL	
OPERATING VOLTAGE RANGE	:4.8V TO 6.0V	
OPERATING TEMPERATURE RANGE	:-20⊠C TO +60⊠C(-68⊠F TO +140⊠F)	
TEST VOLTAGE	:AT 6.0V	AT 7.4V
OPERATING SPEED	:0.15sec/60⊠ AT NO LOAD	0.12sec/60⊠ AT NO LOAD
STALL TORQUE	:24.0kg.cm (333.29oz.in)	30.0kg.cm (416.61oz.in)
STANDING TORQUE	:31.2kg.cm (433.27oz.in)/5⊠ HOLD OUT	39kg.cm (541.59oz.in)/5⊠ HOLD OUT
IDLE CURRENT	:3mA AT STOPPED	3mA AT STOPPED
RUNNING CURRENT	:300mA/NO LOAD RUNNING	380mA/NO LOAD RUNNING
STALL CURRENT	:4200mA	5200mA
DEAD BAND WIDTH	:2usec	2usec
OPERATING TRAVEL	:90⊠9⊠/ONE SIDE PULSE TRAVELING 400usec	
DIRECTION	:CLOCK WISE/PULSE TRAVELING 1500 TO 1900usec	
MOTOR TYPE	:CORELESS METAL BRUSH	
POTENTIOMETER TYPE	:6 SLIDER/INDIRECT DRIVE	
AMPLIFIER TYPE	:DIGITAL AMPLIFIER WITH MOSFET DRIVE	
DIMENSIONS	:40x20x37mm (1.57x0.78x1.45in)	
WEIGHT	:62g(2.18oz)	
BALL BEARING	:DUAL/MR106	
GEAR MATERIAL	:TITANIUM ALLOY	
HORN GEAR SPLINE	:24 SEGMENTS/⊠5.76	
SPLINED HORNS	:REGULAR METAL/R-ML	
CONNECTOR WIRE LENGTH	:300mm (11.81in)	
CONNECTOR WIRE STRAND COUNTER	:60EA	
CONNECTOR WIRE GAUGE	:22AWG	



2.FEATURES

PROGRAMMABLE DIGITAL AMPLIFIER WITH MOSFET DRIVE
DURABLE TITANIUM ALLOY METAL GEARS WITH DUAL BALL BEARING
ULTRA HARDNESS SHAFT WITH 3 AXIAL METAL BUSHING
WATER & DUST TIGHT
BOTTOM SIDE AXIAL MOUNT HOLE

3.APPLICATIONS

ROBOTS

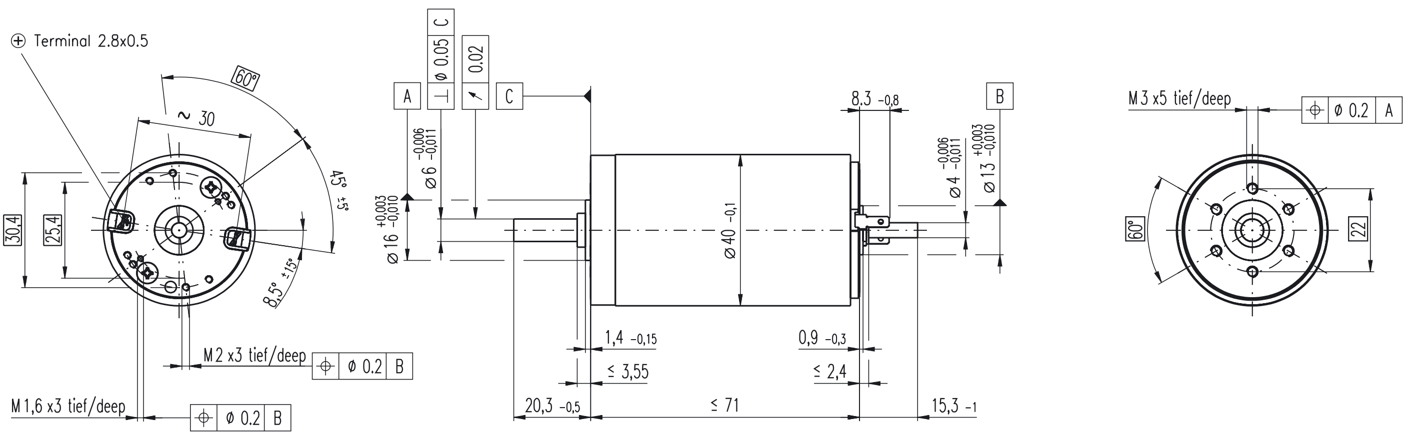
HITEC RCD KOREA INC.

APPENDIX B. MOTOR SPECIFICATION SHEET

Motor specification sheet from:

`http://www.maxonmotorusa.com/files/catalog/2005/pdf/05_083_e.pdf`

RE 40 ∅40 mm, Graphite Brushes, 150 Watt



M 1:2

- Stock program
- Standard program
- Special program (on request!)

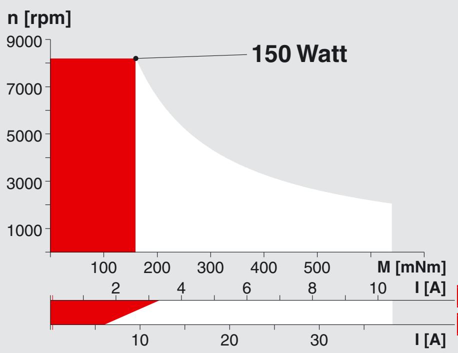
Order Number

		1	2	3	4	5	6	7	8	9	10	11
Order Number		148866	148867	148877	218008	218009	218010	218011	218012	218013	218014	218015
Industrial version		263065	263066	263067	263068	263069	263070	263071	263072	263073	263074	263075
Motor Data												
1 Assigned power rating	W	150	150	150	150	150	150	150	150	150	150	150
2 Nominal voltage	Volt	12.0	24.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0
3 No load speed	rpm	6920	7580	7580	6420	5560	3330	2690	2130	1710	1420	987
4 Stall torque	mNm	1690	2290	2500	1990	1580	996	796	641	512	415	289
5 Speed / torque gradient	rpm / mNm	4.11	3.32	3.04	3.23	3.53	3.36	3.39	3.35	3.37	3.44	3.45
6 No load current	mA	241	137	69	54	44	22	17	13	10	8	5
7 Starting current	A	103	75.9	41.4	28.0	19.2	7.26	4.69	3.00	1.92	1.29	0.627
8 Terminal resistance	Ohm	0.117	0.316	1.16	1.72	2.50	6.61	10.2	16.0	24.9	37.1	76.6
9 Max. permissible speed	rpm	8200	8200	8200	8200	8200	8200	8200	8200	8200	8200	8200
10 Max. continuous current	A	6.00	6.00	3.33	2.75	2.41	1.41	1.13	0.904	0.725	0.594	0.414
11 Max. continuous torque	mNm	98.7	181	201	196	198	193	192	193	193	191	190
12 Max. power output at nominal voltage	W	285	440	491	332	255	86.5	55.7	35.6	22.9	15.3	7.40
13 Max. efficiency	%	88	91	92	91	91	89	88	87	86	85	83
14 Torque constant	mNm / A	16.4	30.2	60.3	71.3	82.2	137	170	214	266	321	461
15 Speed constant	rpm / V	581	317	158	134	116	69.7	56.2	44.7	35.9	29.8	20.7
16 Mechanical time constant	ms	6	5	4	4	4	4	4	4	4	4	4
17 Rotor inertia	gcm²	135	134	134	125	127	118	117	118	117	114	114
18 Terminal inductance	mH	0.02	0.08	0.33	0.46	0.61	1.70	2.62	4.14	6.40	9.31	19.20
19 Thermal resistance housing-ambient	K / W	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
20 Thermal resistance rotor-housing	K / W	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
21 Thermal time constant winding	s	41	40	40	38	38	36	35	35	35	34	34

Specifications

- Axial play 0.05 - 0.15 mm
- Max. **ball bearing** loads
  axial (dynamic)
  not preloaded 5.6 N
  preloaded 2.4 N
  radial (5 mm from flange) 28 N
  Force for press fits (static) 110 N
  (static, shaft supported) 1200 N
- Radial play **ball bearing** 0.025 mm
- Ambient temperature range -20 ... +100°C
- Max. rotor temperature +155°C
- Number of commutator segments 13
- Weight of motor 480 g
- 2 pole permanent magnet
- Values listed in the table are nominal.
  For applicable tolerances see page 43.
  For additional details please use the maxon selection program on the enclosed CD-ROM.

Operating Range



Comments Details on page 49

Recommended operating range

Continuous operation
In observation of above listed thermal resistances (lines 19 and 20) the maximum permissible rotor temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

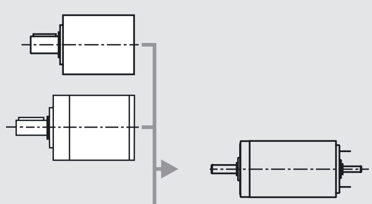
148877 Motor with high resistance winding
148866 Motor with low resistance winding

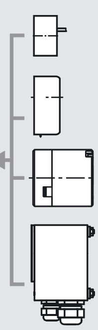
maxon Modular System

Overview on page 17 - 21

Planetary Gearhead
∅42 mm
3 - 15 Nm
Details page 224

Planetary Gearhead
∅52 mm
4 - 30 Nm
Details page 227





Recommended Electronics:

ADS 50/5	page 259
ADS 50/10	259
ADS_E 50/5, 50/10	260
EPOS 24/5, 70/10	271
MIP 50, MIP 100	273
Notes	**17**

Encoder MR
256 - 1024 CPT,
3 channels
Details page 239

Encoder HED_ 5540
500 CPT, 3 channels
Details page 242 / 244

Brake AB
∅40 mm,
24 VDC, 0.4 Nm
Details page 279

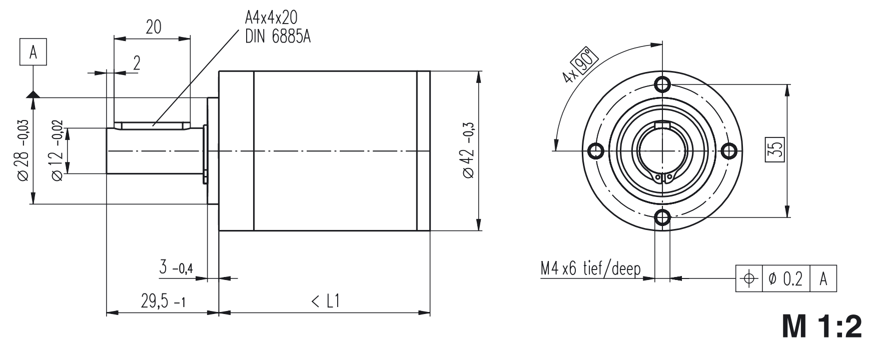
Industrial version
Encoder HEDL 9140
Details page 247
Brake AB
Details page 280

Gearhead specification sheet from:

`http://www.maxonmotorusa.com/files/catalog/2005/pdf/05_224_e.pdf`

Planetary Gearhead GP 42 C ∅42 mm, 3 - 15 Nm

Ceramic Version



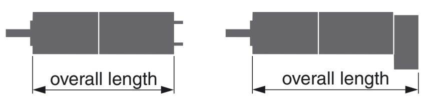
M 1:2

Technical Data

Planetary Gearhead	straight teeth
Output shaft	stainless steel, hardened
Bearing at output	ball bearing
Radial play, 12 mm from flange	preloaded
Axial play	preloaded
Max. permissible axial load	150 N
Max. permissible force for press fits	300 N
Sense of rotation, drive to output	=
Recommended input speed	< 8000 rpm
Recommended temperature range	-20 ... +100°C
Extended range as option	-35 ... +100°C
Number of stages	1 2 3 4
Max. radial load, 12 mm from flange	120 N 150 N 150 N 150 N

Stock program
Standard program
Special program (on request!)

	Gearhead Data		Order Number						
			203113	203115	203120	203125	203128	203134	203139
1	Reduction		3.5 : 1	12 : 1	43 : 1	91 : 1	150 : 1	319 : 1	546 : 1
2	Reduction absolute		7/2	49/4	343/8	91	2401/16	637/2	546
3	Mass inertia	gcm²	14	15	15	15	15	15	14
4	Max. motor shaft diameter	mm	10	10	10	10	10	10	10
	Order Number		203114	203116	203121	203126	203130	203135	203140
1	Reduction		4.3 : 1	15 : 1	53 : 1	113 : 1	186 : 1	353 :1	676 : 1
2	Reduction absolute		13/3	91/6	637/12	338/3	4459/24	28561/81	676
3	Mass inertia	gcm²	9.1	15	15	9.4	15	9.4	9.1
4	Max. motor shaft diameter	mm	8	10	10	8	10	8	8
	Order Number			203117	203122	203127	203131	203136	203141
1	Reduction			19 : 1	66 : 1	126 : 1	230 : 1	394 : 1	756 : 1
2	Reduction absolute			169/9	1183/18	126	8281/36	1183/3	756
3	Mass inertia	gcm²		9.4	15	14	15	15	14
4	Max. motor shaft diameter	mm		8	10	10	10	10	10
	Order Number			203118	203123	203129	203132	203137	203142
1	Reduction			21 : 1	74 : 1	156 : 1	257 : 1	441 : 1	936 : 1
2	Reduction absolute			21	147/2	156	1029/4	441	936
3	Mass inertia	gcm²		14	15	9.1	15	14	9.1
4	Max. motor shaft diameter	mm		10	10	8	10	10	8
	Order Number			203119	203124		203133	203138	
1	Reduction			26 : 1	81 : 1		285 : 1	488 : 1	
2	Reduction absolute			26	2197/27		15379/54	4394/9	
3	Mass inertia	gcm²		9.1	9.4		15	9.4	
4	Max. motor shaft diameter	mm		8	8		10	8	
5	Number of stages		1	2	3	3	4	4	4
6	Max. continuous torque	Nm	3.0	7.5	15	15	15	15	15
7	Intermittently permissible torque at gear output	Nm	4.5	11.3	22.5	22.5	22.5	22.5	22.5
8	Max. efficiency	%	90	81	72	72	64	64	64
9	Weight	g	260	360	460	460	560	560	560
10	Average backlash no load	°	0.6	0.8	1.0	1.0	1.0	1.0	1.0
11	Gearhead length L1	mm	40.9	55.4	69.9	69.9	84.4	84.4	84.4



Combination

+ Motor	Page	+ Tacho / Encoder	Page	+ Brake	Page	Overall length [mm] = Motor length + gearhead length + (tacho / encoder / brake) + assembly parts						
RE 35, 90 W	81					111.9	126.4	140.9	140.9	155.4	155.4	155.4
RE 35, 90 W	81	MR	239			123.3	137.8	152.3	152.3	166.8	166.8	166.8
RE 35, 90 W	81	HED_ 5540	242/244			132.9	147.4	161.9	161.9	176.4	176.4	176.4
RE 35, 90 W	81	DCT 22	252			130.0	144.5	159.0	159.0	173.5	173.5	173.5
RE 35, 90 W	81			AB 40	279	148.0	162.5	177.0	177.0	191.5	191.5	191.5
RE 36, 70 W	82					112.2	126.7	141.2	141.2	155.7	155.7	155.7
RE 36, 70 W	82	MR	239			123.6	138.1	152.6	152.6	167.1	167.1	167.1
RE 36, 70 W	82	HED_ 5540	242/244			133.2	147.7	162.2	162.2	176.7	176.7	176.7
RE 36, 70 W	82	DCT 22	252			130.3	144.8	159.3	159.3	173.8	173.8	173.8
RE 40, 150 W	83					112.0	126.5	141.0	141.0	155.5	155.5	155.5
RE 40, 150 W	83	MR	239			123.4	137.9	152.4	152.4	166.9	166.9	166.9
RE 40, 150 W	83	HED_ 5540	242/244			132.7	147.2	161.7	161.7	176.2	176.2	176.2
RE 40, 150 W	83	HEDL 9140	247			166.1	180.6	195.1	195.1	209.6	209.6	209.6
RE 40, 150 W	83			AB 40	279	148.1	162.6	177.1	177.1	191.6	191.6	191.6
RE 40, 150 W	83			AB 28	280	156.1	170.6	185.1	185.1	199.6	199.6	199.6
RE 40, 150 W	83	HED_ 5540	242/244	AB 40	279	165.2	179.7	194.2	194.2	208.7	208.7	208.7
RE 40, 150 W	83	HEDL 9140	247	AB 28	280	176.6	191.1	205.6	205.6	220.1	220.1	220.1
EC 40, 120 W	160					111.0	125.5	140.0	140.0	154.5	154.5	154.5
EC 40, 120 W	160	HED_ 5540	243/245			129.4	143.9	158.4	158.4	172.9	172.9	172.9
EC 40, 120 W	160	Res 26	253			137.6	152.1	166.6	166.6	181.1	181.1	181.1
EC 40, 120 W	160			AB 24	279	141.8	156.3	170.8	170.8	185.3	185.3	185.3
EC 45, 150 W	161					152.2	166.7	181.2	181.2	195.7	195.7	195.7
EC 45, 150 W	161	HEDL 9140	247			167.8	182.3	196.8	196.8	211.3	211.3	211.3
EC 45, 150 W	161	Res 26	253			152.2	166.7	181.2	181.2	195.7	195.7	195.7
EC 45, 150 W	161			AB 28	280	159.6	174.1	188.6	188.6	203.1	203.1	203.1
EC 45, 150 W	161	HEDL 9140	247	AB 28	280	176.6	191.1	205.6	205.6	220.1	220.1	220.1

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